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HOT ACCRETION ONTO WHITE DWARFS IN QUIESCENT DWARF NOVAE

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ABSTRACT

We present dynamically consistent solutions for hot accretion onto unmagnetized, rotating white dwarfs (WDs) in five quiescent dwarf novae. The measured WD rotation rates (and other system parameters) in RX And, SS Cyg, U Gem, VW Hyi and WZ Sge imply spindown of the WD by an extended hot flow emitting most of its X-rays in the vicinity of the stellar surface. In general, energy advection is absent and the flow is stable to convection and hydrodynamical outflows. In rapidly rotating systems, the X-ray luminosity provides only an upper limit on the quiescent accretion rate because of substantial stellar spindown luminosity. We suggest that the presence of hot flows in quiescent dwarf novae may limit the long-term WD rotation rates to significantly sub-Keplerian values.

Subject headings: X-ray: stars – binaries: close – accretion, accretion disks – stars: white dwarfs

1. INTRODUCTION

Dwarf novae (DN) are accreting binary star systems with a white dwarf (WD) primary fed by a main-sequence donor via Roche-lobe overflow. They represent a subclass of cataclysmic variables (CVs) and experience semiregular, luminous outbursts, during which accretion onto the WD proceeds at a high rate. Most of the time, however, DN are in quiescence — a phase during which the accretion rate onto the WD (and the system luminosity) is considerably reduced (see Warner 1995 for a review). According to the disk instability model (DIM), such a behavior arises because most of the mass transferred by the companion star builds up in an unsteady disk during quiescence (Cannizzo 1993; Lasota 2001).

Quiescent DN are hard X-ray sources with typical luminosities of $\sim 10^{30}-10^{32}$ erg s^{-1} (see, e.g., Córdova & Mason 1983; Patterson & Raymond 1985). Spectral fits to this X-ray emission suggest a Bremsstrahlung origin from gas with temperatures $\sim 2-20$ keV (Patterson & Raymond 1985; Eracleous et al. 1991; Belloni et al. 1991; Yoshida et al. 1992; Mukai & Shiokawa 1993). This X-ray emission is commonly attributed to the boundary layer (BL) at the interface between the WD and the thin accretion disk around it. At low accretion rates ($\lesssim 10^{16}$ g s^{-1}, typical of quiescent DN), the gas in the BL is hot and optically thin, hence it is a substantial source of hard X-ray emission (Pringle & Savonije 1979; Tylenda 1981; Patterson & Raymond 1985). Detailed calculations by Narayan & Popham (1993) show that the optically-thin BLs of disk-accreting WDs can also be radially extended (of order a WD radius) and that energy advection is an important element of their internal structure.

On the other hand, Meyer & Meyer-Hofmeister (1994) presented two arguments in favor of a more extended, inner hot flow structure in quiescent DN. They noted that: (i) the standard DIM predicts accretion rates at the WD surface which are smaller than those inferred from quiescent X-ray luminosities by typically more than one order of magnitude and (ii) the presence of an extended, low-density hot flow in the WD vicinity may explain the observed delay (of $\sim 0.5-1$ day) in the rise to outburst of the EUV light relative to the optical light (e.g., Mauche, Mattei & Bateson 2001, but see Smak 1998). Our current understanding of the structure and properties of quiescent disks is rather limited (Menou 2002), so studying the possible presence of an extended, hot flow in quiescent DN is certainly worthwhile.

Recently, Medvedev & Narayan (2001a) discovered solutions for hot accretion onto unmagnetized, rotating compact stars. They found that at large stellar spin rates, dissipation in the hot flow is dominated by stellar braking in a "hot settling flow" (HSF) configuration, whereas in the opposite limit, the flow reduces to a conventional advection-dominated accretion flow (ADAF; Narayan & Yi 1994; 1995). Both flows exist at relatively low accretion rates ($\lesssim 10^{-2}$ of Eddington). Medvedev & Narayan (2001b) have also addressed the thermal stability of their (cooling-dominated) settling solution, and found that it is most likely stable, once turbulent thermal conduction is accounted for. The work of Medvedev & Narayan was largely focused on accretion onto neutron stars, but the HSF solutions are also valid for WD accretion. This is important because, in general, much more is known about WDs in CVs than about neutron stars in close binary systems. In particular, the rotation rates of several WDs in DN have been measured during the last few years thanks to *HST* spectroscopy (see Sion 1999 for a review). In this *Letter*, we apply the model of Medvedev & Narayan to WDs in quiescent DN by constructing numerical solutions for hot accretion in five systems with relatively well known system parameters.

2. SYSTEM PARAMETERS

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We have gathered existing data on quiescent DN for which estimates of the WD rotation rate and the quiescent X-ray luminosity were both available. A summary of the system parameters adopted for this study is given in Table 1. For the WD masses, $M_{\rm wd}$, and orbital inclinations, i, we uniformly adopt the values given in the catalog of Ritter & Kolb (1998). To derive the WD rotation rates, we use the observationally inferred values of $V_{\rm rot} \sin i$ compiled by Sion (1999) and make the assumption that the stellar rotation axis is aligned with the rotation axis of the orbital motion. A spin parameter, s, can then be calculated as the ratio of $V_{\rm rot}$ to the Keplerian rotation rate at the WD radius, $V_{\rm K}(R_{\rm wd})$. For the WD radii, we simply use the reasonable mass–radius relation: $R_{\rm wd} = 5 \times 10^8$ cm $(M_{\rm wd}/1.2\ {\rm M}_\odot)^{-0.33}$. Finally, references from which quiescent X-ray luminosities were collected can be found in Table 1. When several values existed for a given system, we generally adopted the value corresponding to the hardest X-ray spectral range (given the typically hard Bremsstrahlung spectrum of quiescent DN). Note that the accuracy of the system parameters adopted is not crucial because we only wish to illustrate the general properties of hot accretion in these systems.[2]

3. HOT ACCRETION SOLUTIONS

To investigate the nature of hot accretion in quiescent DN, we use the numerical code described in detail by Medvedev & Narayan (2001a). We solve the height-integrated, axisymmetric hydrodynamical equations for the conservation of mass, radial and angular momenta, and two energy equations for the proton and electron fluids. These equations are solved by the relaxation method with appropriate boundary conditions. A special grid was used to carefully resolve steep gradients near the stellar surface. At the outer boundary, the electron and proton temperatures and the angular velocity of the flow are fixed to the values appropriate for an ADAF. At the inner boundary, where the flow meets the stellar surface, the flow temperature and the angular velocity are forced to match those of the star. We assume a stellar temperature of $\sim$ few$\times 10^5$ K (the exact value is unimportant here). The mass accretion rate, $\dot{M}$, is a free parameter, and a standard Shakura-Sunyaev α-viscosity is used. We assume that most of the viscously generated heat goes to protons. However, this is unimportant because the electrons are coupled to the protons via Coulomb collisions very efficiently. The electrons are cooled via optically thin Bremsstrahlung emission. Thermal conduction and (self-absorbed) synchrotron cooling are not included, for simplicity (the latter should be negligible). The effects of Comptonization of the stellar radiation and self-Comptonization of the Bremsstrahlung radiation are included, but both are very weak. We generally adopt an adiabatic index $\gamma = 1.6$, close to the $\gamma = 5/3$ of a non-relativistic, monoatomic ideal gas. In all models we choose the outer radius of the flow to be at $\sim$ few $\times 10^{11}$ cm to better isolate the effects of the inner and outer boundary conditions. In real systems, the outer radius is probably much smaller. The adopted parameters, namely the stellar mass, $M_{\rm wd}$, its radius, $R_{\rm wd}$, and its spin parameter, s, are given in Table 1. In all systems but WZ Sge, we used a conventional value of the viscosity parameter, $\alpha = 0.1$. In WZ Sge we set $\alpha = 0.02$, as discussed below.

Figure 1 shows the numerical solutions obtained for the five systems listed in Table 1. In each case, the accretion rate in the steady, hot flow has been adjusted so that the total Bremsstrahlung emission fits the quiescent X-ray luminosity given in Table 1. The four panels in Figure 1 show the radial profiles of density, ρ (in g cm^{-3}), electron and proton temperatures, T_e and T_p respectively (in Kelvin; the curves overlap because $T_e \approx T_p$ indicating efficient Coulomb transfer of energy between the ions and the electrons), angular rotation velocity, Ω (in units of the Keplerian value at the WD radius, $\Omega_K(R_{\rm wd})$) and radial velocity, V_R (in units of the speed of light, c). The profiles are approximate power laws, with narrow boundary layers close to the WD surface (except for Ω, which smoothly matches the stellar rotation rate). The profiles of Ω and V_R indicate that boundary effects are present over a substantial range of radii, at both the inner and outer edges.

The scalings in an ADAF are $\rho \propto R^{-3/2}$ and $V_R \propto R^{-1/2}$ (Narayan & Yi 1994), while in a HSF they are $\rho \propto R^{-2}$ and $V_R \propto R^0$ (Medvedev & Narayan 2001a). The profiles of ρ and V_R in Fig. 1 deviate from perfect power laws and are intermediate between the above two solutions. The Bernoulli number is negative everywhere (for $\gamma \sim 5/3$), except in a narrow region at the outer edge of the flow where the ADAF conditions hold (in an ADAF, $Be > 0$). Hence, the solutions should be convectively stable (Narayan et al. 2000; Medvedev & Narayan 2001a).

The solutions shown in Fig. 1 are not "advection-dominated" in the sense that the gas entropy decreases inward (it increases inward in an ADAF). The flow energetics is best described by computing the ratio of the integrated Bremsstrahlung luminosity to the available accretion luminosity, $L_{\rm acc} = G M_{\rm wd} \dot{M} / R_{\rm wd}$. The accretion rates for the five systems are quite low (Table 1). The corresponding ratios, $\eta_{\rm eff} \equiv L_X / L_{\rm acc}$, are ~ 1 for low-s systems and larger than unity for large s, indicating significant extraction of rotational energy from the central star. Thus, in large-s systems such as WZ Sge, the $\dot{M}$ value given in Table 1 should be considered as a rough upper limit because L_X is essentially powered by stellar spindown with little contribution from the accretion luminosity. However, the luminosity of a HSF is sensitive to α. We were able to fit the observed L_X of WZ Sge only for $\alpha \approx 0.02$. Perhaps, this may indicate that the value of α may be lower than generally expected.

The value of the adiabatic index has a strong effect on the flow structure. We illustrate this by calculating a model for U Gem with $\gamma = 4/3$ (all other parameters being the same). It is shown in Fig. 1 as a thick solid line. At large radii, the flow structure now adopts an ADAF configuration, with $\rho \propto R^{-3/2}$, $V_R \propto R^{-1/2}$ and a larger, constant value of Ω/Ω_K. The Bernoulli number is positive everywhere in the hot flow (excluding the BL) and energy advection is dominant in the outer regions of the flow with ADAF properties. However all the advected energy is now radiated in the optically thin BL so that $\eta_{\rm eff} \approx 1$ as well. This influence of γ is consistent with the results

[2]For instance, even if the WD in WZ Sge was much more massive than assumed in Table 1 (e.g. Steeghs et al. 2001), it would still be the fastest rotator among all five systems, as measured by the s parameter.

of Medvedev & Narayan (2001a). According to their classification, the solutions we obtained for $\gamma = 1.6$ and the inner zone of the flow in the case with $\gamma = 4/3$ are "settling ADAFs" (WZ Sge clearly corresponds to a HSF, however).

Fig. 2 shows the Bremsstrahlung luminosity, per unit logarithmic fractional distance from the WD surface, for the five solutions with $\gamma = 1.6$ shown in Fig. 1. The density in the flow is low enough that Comptonization has a negligible effect on the emitted spectrum, even in the densest regions, near the WD surface. Fig. 2 clearly shows that X-ray emission originates mostly from regions in the close vicinity of the WD (the same is true for the U Gem model with $\gamma = 4/3$). The brightest regions of the flow are also approximately the hottest, with temperatures $\simeq 10^8$ K for WZ Sge, $\simeq 2 \times 10^8$ K for VW Hyi and $\simeq 4 \times 10^8$ K for the three other systems.

4. DISCUSSION

We constructed numerical models for hot accretion onto unmagnetized, rotating WDs in five quiescent DN. Our solutions are a significant improvement over previous work on hot accretion in this context (Katz 1977; Kylafis & Lamb 1982; Mahasena & Osaki 1999; Menou 2000) in that both the WD rotation and the viscous nature of the flow are accounted for in the present case. This makes these solutions plausible modes of accretion in quiescent DN.

The outer boundary conditions chosen are somewhat artificial and constitute a significant shortcoming of the present study. It is unclear exactly how the transition from an inner hot flow to an outer thin disk (known to be present) would occur. Strong boundary effects may be expected for a hot flow with a limited radial extent. Nonetheless, our work has the virtue of isolating the main properties of the hot flow, independently of the disk. It will be important in the future to study the structure of a hot flow with a smaller radial extent and more realistic boundary conditions. For the non-relativistic gas considered here and non-dominant magnetic fields, we expect rather large values of γ and therefore flows which are not subject to outflows (Blandford & Begelman 1999) or convection (Narayan et al. 2000; Quataert & Gruzinov 2000).

Menou (2000) proposed that energy advection in a hot flow could be important in powering a dominant EUV emission component that could explain the strong He II emission lines observed in many quiescent DN. Since the hot flow solutions presented here lack energy advection (for γ's near 5/3), this possibility seems unlikely.

While a star is spun up by accretion via a disk boundary layer (except when rotating near breakup; Popham & Narayan 1991; Paczynski 1991), it is spun down when accreting via a hot flow like an ADAF, a HSF or the hot flow solutions presented here (except at very low spin rates; Medvedev & Narayan 2001a). This property has potentially important consequences for the spin history of WDs in DN. Sion (1999) emphasized that in the standard picture WDs should rotate near break up in DN, but observations suggest that rapidly spinning WDs are rare. If a WD is spun down via hot accretion during quiescence, an equilibrium at substantially sub-Keplerian rotation rates may be expected from the balance between spin-up in outburst and spin-down in quiescence. This possibility requires further study with more appropriate boundary conditions. We note that other mechanisms could contribute to spinning down single WDs (Spruit 1998) and WDs in DN (and thus get rid of the angular momentum acquired during accretion), including angular momentum losses induced by coupling to an expanding envelope during nova explosions (Livio & Pringle 1998; Sion et al. 2001).

X-ray eclipses in several quiescent DN indicate that the emission originates from the vicinity of the WD (Wood et al. 1995; Mukai et al. 1997; Pratt et al. 1999; Ramsay et al. 2001). Without a detailed comparison, it is unclear whether the hot flow solutions presented here satisfy the existing observational constraints or not. Such a comparison should take into account the spectral coverage of the various X-ray instruments used and it probably requires a reliable boundary layer model taking into account the role of heat conduction in potentially modifying its emission properties (which is beyond the scope of the present paper). It is certainly encouraging that X-ray emission is highly concentrated near the stellar surface in our models, but it is presently unclear whether these models will be able to account for the available X-ray eclipse data or not. We note, for instance, that the X-ray eclipse of OY Car observed by Ramsay et al. (2001) suggest an X-ray flux approaching zero at eclipse minimum and a small vertical extent for the X-ray emitting region. These properties may not be easily reconciled with the hot flow models presented here. In the future, it will also be possible to probe the structure of hot flows in (even non-eclipsing) quiescent DN with detailed X-ray spectroscopic diagnostics, as illustrated in Menou, Perna & Raymond (2001; see also Narayan & Raymond 1999).

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TABLE 1
SYSTEM PARAMETERS

System name	$M_{\rm wd}$ ($M_\odot$)	$R_{\rm wd}$ (10^8 cm)	i ($^\circ$)	$V_{\rm rot}$ (km s^{-1})	s ($V_{\rm rot}/V_{\rm K,wd}$)	L_X (erg s^{-1})	$\dot{M}$ (g s^{-1})	$\eta_{\rm eff}$ ($L_X/L_{\rm acc}$)
RX And	1.14	5.1	51°	190	0.03	3×10^{31} [a]	10^{14}	1.0
SS Cyg	1.19	5.0	37°	500	0.09	10^{32} [b]	3.3×10^{14}	1.0
U Gem	1.26	4.9	70°	≤ 110	≤ 0.02	10^{31} [c]	3×10^{13}	1.0
VW Hyi	0.63	6.2	60°	460	0.13	7×10^{30} [d]	3.5×10^{13}	1.5
WZ Sge	0.45	7.0	75°	1240	0.42	3×10^{30} [e]	1.1×10^{13}	3.2

NOTE. – (a) Eracleous, Halpern & Patterson (1991) (b) Yoshida, Inoue & Osaki (1992); Mukai & Shiokawa (1993) (c) Szkody et al. (1996) (d) Mukai & Shiokawa (1993); Eracleous et al. (1991) (e) Eracleous et al. (1991); Mukai & Shiokawa (1993).

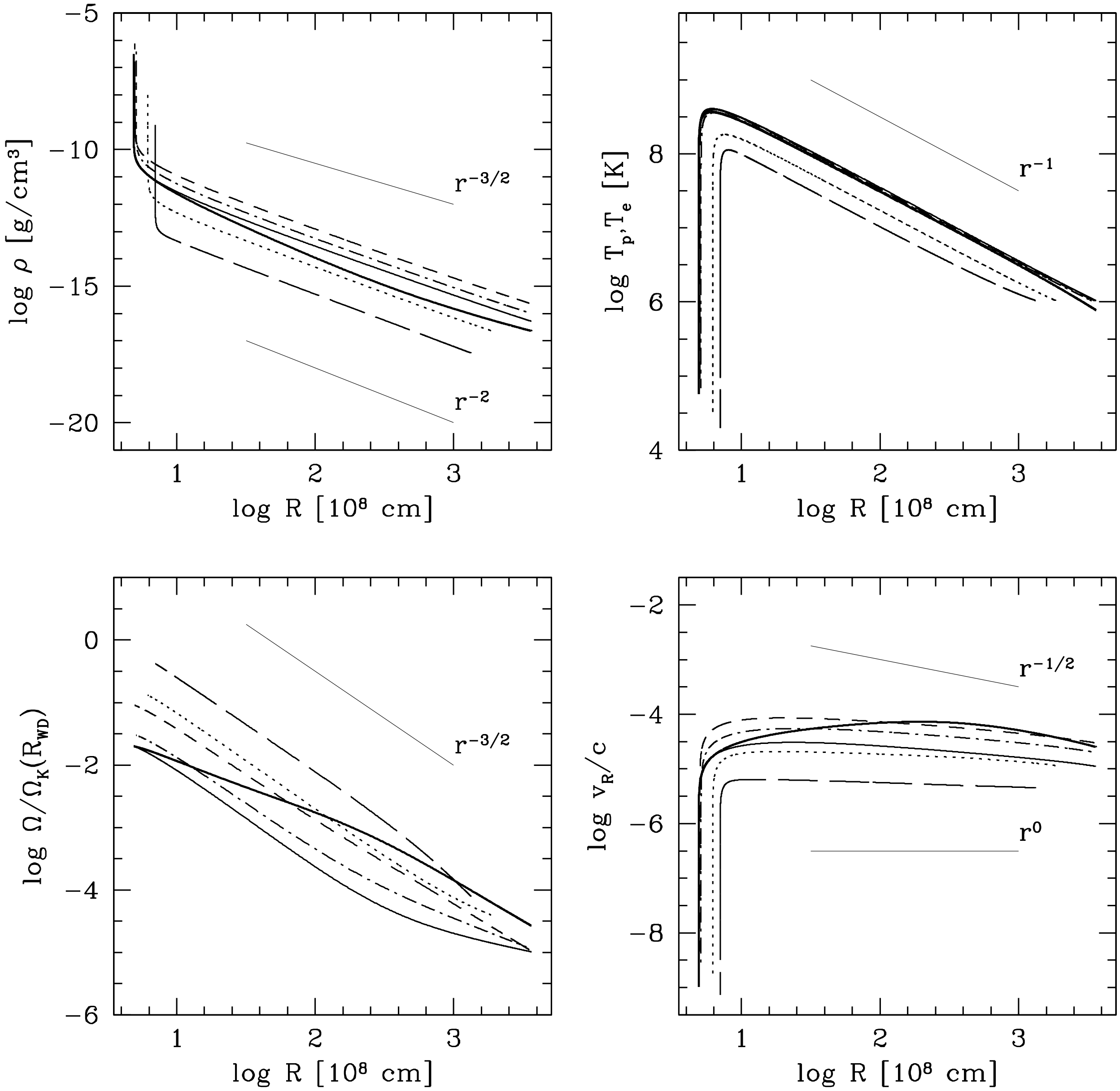

FIG. 1.— Radial profiles of density, ρ, proton and electron temperatures, T_p and T_e, angular rotation velocity, Ω, and radial velocity, V_R, for hot accretion with $\gamma = 1.6$ in the five systems listed in Table 1 (RX And: dot-dashed, SS Cyg: short-dashed, U Gem: thin solid, VW Hyi: dotted, WZ Sge: long-dashed). The density profiles for VW Hyi and WZ Sge have been scaled down by a factor 10 and 100, respectively. The thick solid line correspond to the same model for U Gem except that $\gamma = 4/3$ instead of 1.6.

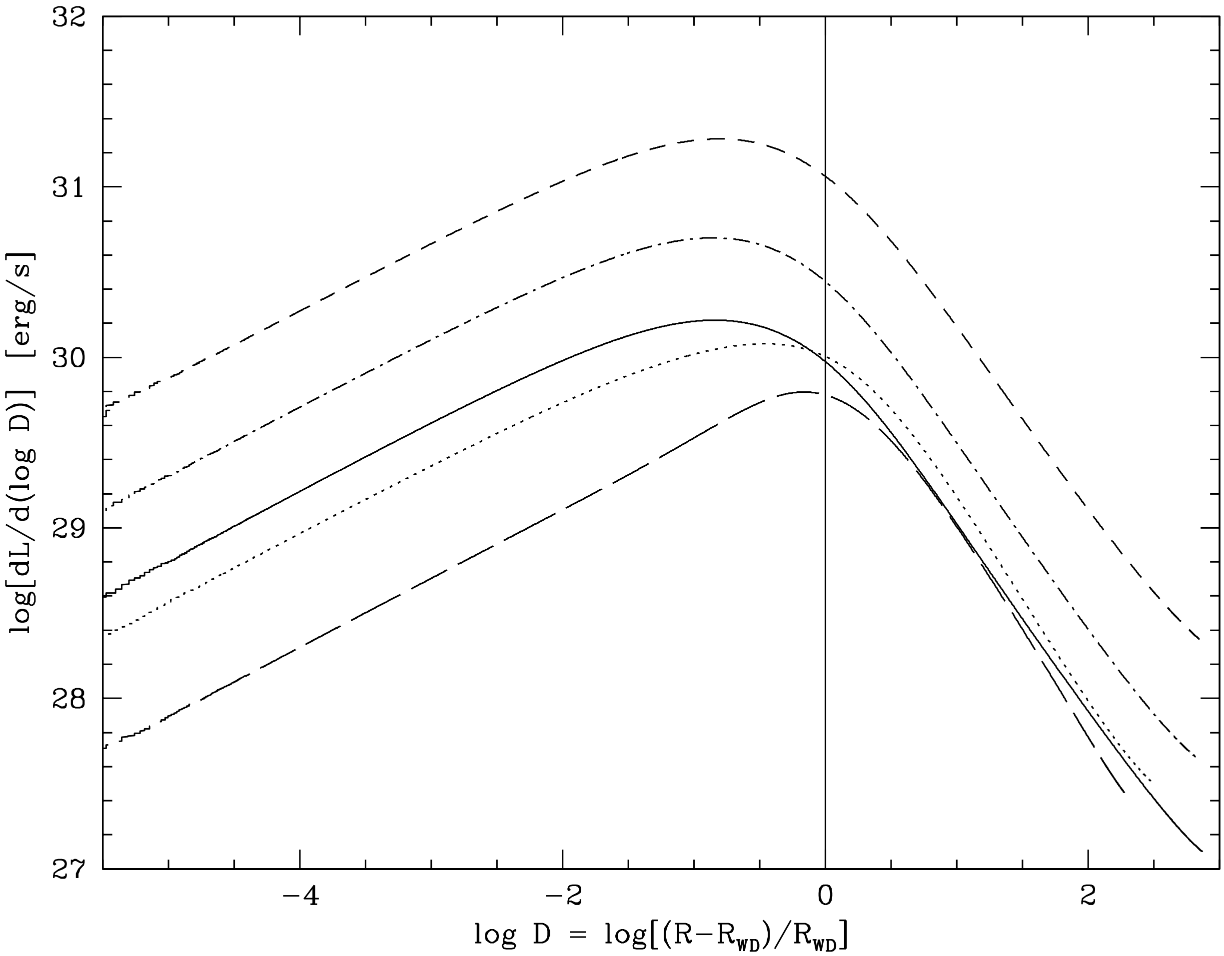

FIG. 2.— Bremsstrahlung luminosity of the hot flow, per unit logarithmic fractional distance from the white dwarf surface, for the five models with $\gamma = 1.6$ shown in Fig 1 (same notation). Most of the X-ray emission originates from the white dwarf vicinity.